CEPHEID DISTANCES TO NEARBY GALAXIES:
V. GROUND-BASED PHOTOMETRY OF M81

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ABSTRACT

Using the Canada-France-Hawaii Telecope (CFHT) we have obtained three closely spaced epochs of calibrated BVRI CCD imaging of two fields in M81, each known to contain a thirty-day Cepheid. Under the assumption that the two Cepheids are representative, the multi-wavelength BVRI period-luminosity moduli show evidence for only a slight reddening, E(B –V) ~ 0.03 – 0.04 msg. The Cepheid-derived true distance modulus to M81 is determined to be (m – M). = 27.75 mag, corresponding to a linear distance of 3.5 Mpc. An error analysis shows that the derived distance modulus has a *random error* of ±0.28 mag (due to the photo metric uncertainties in the BVRI data) and a *systematic uncertainty* of ±0.10 mag (due to the combined effects of unknown phasing and the unknown positioning of these stars within the Cepheid instability strip.)

Calibrated BVRI photometry of the brightest stars in these same Cepheid fields is also presented. The position of the blue plume in the color-magnitude diagrams of the surrounding M81 field population indicate a general field reddening, in the range E(B - V) ~ 0.05 - 0.14 mag. The slope of the luminosity function from the brightest 3-4 mag of the blue Plume is consistent with similar determinations of the apparent luminosity function in other resolved galaxies, thereby removing the one potential deviation from universality noted by Freedman (ApJ, 299, 74, 1985) in her photographic study of luminosity functions in nearby resolved galaxies.

Subject headings: galaxies: individual (M81) galaxies: distances stars: Cepheids

1. INTRODUCTION

The spiral galaxy M81 continues to be important calibrator for a number of secondary methods used in the extragalactic distance scale (see Freedman and Madore 1992 and references therein for a recent overview). And the discovery of SN 1993J in that galaxy (Ripero 1993) only heightens the interest in independently knowing this galaxy's true distance modulus. Finally, in anticipation of the complementary Cepheid observations being made by the *Hubble Space Telescope* (HST), we present the following multi-wavelength analysis of our remaining, calibrated ground-based data on two of the known Cepheids in M81 and the surrounding resolved stellar populations.

In the mid 1980's we began a program at the CFHT aimed at monitoring fields in the galaxies M81 and M101, with the intention of discovering new Cepheid variables in these systems, and at the same time determining time-averaged magnitudes and multi-wavelength colors at least for the two known 30-day Cepheids in M81 (Sandage, private communication). Such observations were designed to better define the reddenings to these variables and thereby provide more accurate distances to the galaxies as a whole. in the first season, data were obtained in four bandpasses on three consecutive nights. But subsequent seasons were not awarded time. Accordingly, we were left with a small and incomplete data set which was neither sufficient for the purposes of discovering new Cepheids nor extensive enough to unequivocally define mean properties of the known ones. It was our hope to supplement these observations over the years at other telescopes, but unfortunately the weather has not been kind to this project.

Nevertheless, the present observations do contain information (calibrated shorter wavelength optical magnitudes and colors) that go well beyond the single-epoch I-band data points that we published some years ago (Freedman aud Madore 1988). '1'here wc presented the first evidence that M81 is in fact at a distance of approximately 3.3 Mpc ((m – M) = 27.6 mag). This is much smaller than the apparent B modulus of 28.8 mag being advocated at that time by Sandage (1984); but it is very similar to the distance of its nearby neighbor NGC 2403, for which wc also published, in that same study, a statistically more secure I-band Cepheid distance of 3.2 Mpc ((m – M) = 27,5 mag), based on 8 Cepheids.

II. OBSERVATIONS ANI) DATA REDUCTION

When we first embarked on this project, finder charts and periods for the two 30-day Cepheids in M81 were very kindly supplied to one of us (WLF) by Allan Sandage. The identifications of those fields surrounding the Cepheids arc given in Figure 1. BVRI CC]) frames, obtained at the CFHT on three consecutive nights in **198*, we re reduced in the same! manner as described in Wilson, Freedman and Madore (1990), being tied to the standard Kron-Cousins system using Landolt (. 983) photoelectric Standards for the extinction and transformation equations.

The Cepheid data for variables V2 and V30 are given in 'J'able 1; and photometry for the several hundred of the brightest stars in each of tile two Cepheid fields are given in Tables 2 and 3. The latter observations have proven to be especially important in tying down the absolute calibration of our 11 S'1' Wide-l~ield Camera observations of an over-lapping Cepheid search field in this galaxy. The data are presented here in anticipation and in aid of that more extensive search for Cepheids in M81 using 11 ST (Freedman *et al.* 1994). and as a follow-up to the single wavelength study of Freedmans & Madore (198 S).

III. THE MULTI-WAVELENGTH PERIOD-LUMINOSITY RELATIONS

Given only three closely spaced BVRI observations of just two Cepheids is there any point in attempting to derive a true distance modulus to M81? In the following we will show that even with only two Cepheids in the sample a quantitative (systematic and random) error analysis shows that the results are robust and precise at the 10-percent level in distance.

Case A We begin here by considering the case where the two Cepheids are representative of the mean; that is, (1) the intensity-averaged magnitudes of the three observed data points per star are representative of the true mean magnitudes of the Cepheids, and (2) the average of the two Cepheids' mean magnitudes is in turn close to the central ridge line of the instability strip.

Under these assumptions the resulting apparent moduli are $(m-M)_B = 27.88$, $(m-M)_V = 27.96$, $(m-M)_R = (m-M)_I = 27.94$ mag. They were derived by minimizing the residuals between the fiducial LMC long-period Cepheid data set described in Madore and Freedman (1990) using $E^{LMC}_{B-V} = 0.17$ mag and $(m-M)^{LMC}_0 = 18.50$ mag. The apparent moduli, plotted as a function of inverse wavelength, are shown in Figure 1. Because the data points at each of the four wavelengths are for the same Cepheids, the data points are strongly correlated (through their effective temperatures and through their reddenings). The solid line is a standard Galactic extinction law (Cardelli *et al.* 1989) scaled and fitted to that correlation: the scaling gives $E^{M81}_{B-V} = 0.035$ mag, and the intercept at $1/\lambda = 0.0$ gives $(m-M)_0 = 27.75$ mag.

a) Systematic Error Analysis

To assess the *systematic errors* that might result from the aforementioned set of default assumptions we now examine some extreme cases involving maximum deviations away from mean light and maximum displacement from the ridge line of the period-luminosity (PL) relation,

Both the width of the instability strip and the luminosity amplitudes of Cepheids decrease with increasing wavelength. Scaling relations for these quantities as a function of wavelength are well known (see Madore and Freedman 1991 for the latest absolute width for the instability strip at a variety of wavelengths, and sec Freedman 1988 for a calibration of the amplitude ratios). For instance, in the blue, the full width of the period-luminosity relation is about 1.50 mag (Madore and Freedman 1991), such that a star residing on the red (blue) edge of the instability strip would appear 0.75 mag fainter (brighter) than the ridge-line mean. In addition, given a B amplitude of 1.2 mag for a typical Cepheid, that same red-edge (hluc-edge) star can be yet another 0.6 mag fainter (brighter) than the ridge line if observed at minimum (maximum) light. The total apparent modulus error in B could then be 1.:35 mag, or about a factor of two in derived distance, if no corrections for reddening were applied. Scaling these B magnitude examples to the remaining three wavelengths and examining a few extreme combinations we present three additional interpretations of the M81 data in deriving reddenings and true moduli:

Case 13 At mean light the two Cepheids intrinsically reside on the central ridge line of tile PL relation, but the stars arc both coincidentally sewn at maximum light. To accommodate this possibility semi-amplitude off-sets of 0.60, 0.40, 0.26 and ().'20 mag were applied to the BVRI data points respectively, and the fitting procedure re-applied. Interpreting the residuals resulting as being due solely to reddening gives $(m - M)_0 =$ **27.60** mag, with $E(B - V) =$ **0.22** msg.

Case C Here **wc** assume that the average of the Cepheid data points are observed near their mean magnitudes, but now the two stars reside intrinsically on the blue side of the instability strip. Half-strip-width off-sets of 0.72, 0.54, 0.44 and 0.36 mag respectively, were applied to the BVRI data points to simulate the effect of this assumption. Fitting the resulting residuals to a reddening law gives $(m - M)_0 = 27.81$ mag, with $E(B - V) = 0.20$ mag.

case B + C In this most extreme case tile two Cepheids intrinsically reside on the blue side of the 1'1, relation, and they are both simultaneously passing through maximum light. Combined amplitude and strip position ofr-sets as given above (1 .32, 0.94, 0.70 and 0.56 mag, respectively) were adopted. The resulting distance modulus and reddening fit gives (m – M). = 27.62 mag and E(B – V) = 0.38 mag, required to make the stars appear to be unreddened as they do in Figure * when treated as in Case A.

For the presently available M81 data, the derived apparent B moduli, under the various (and extreme) assumptions given above, range from 27.88 mag (assuming the stars are at the mean in all respects) to 29.20 mag (if it is assumed that the stars arc maximally bright). But almost the full impact of these effects on the apparent distance moduli are compensate.d for by the methodology employed in accounting for reddening and deriving a true modulus. This is because of the closely parallel (almost degenerate) tracking of Cepheid colors with effective temperature and with reddening. Correcting for any one effect simultaneously tends to corrects for the others. This is graphically demonstrated in Figure *, where the resulting fits for the four cases discussed above arc shown assuming that only reddening is causing the deviations, but it nevertheless corrects for amplitude and/or strip positioning. While the *apparent moduli* are very different, the scatter in the derived true modulus is a factor of six smaller than the B-band solutions, having a *total range* of only 0.2 mag.

With the total range quoted above equated to a two-sigma estimator of the error in tile true modulus, as induced by systematic errors (in the strip position and phasing assumptions) then wc conclude that a single Cepheid (with an *a priori* known period) observed at one phase, in at least two, well separated wavelengths can give a true distance modulus good to ±0.1 msg. Such an error will scale down further with <hi, where for small samples, N can be either the number of Cepheids or the number of randomly chosen observations of a given Cepheid.

b) Random Photometric Error Propagation

Having considered several potential sources of systematic error the following analysis indicates that the dominant source of uncertainty in deriving a true distance modulus to M81 is the photometric accuracy of the data point themselves.

To assess the numerical importance of these (random) errors on the derived true distance modulus wc performed the following test using the data at hand: For each set of simultaneous BVRI observations of each star (i. e., BVRI photometry on three nights of two stars = six sets in all) wc independently determined reddening/distance modulus solutions using the multi-wavelength fitting procedure. The average of the six true moduli determined in this way is $(m - M) = 27.76 \pm 0.28$ mag, with an average reddening of $E(B - V) = 0.05 \pm 0.07$ mag.

A comparison of this random-photometric-error-induced uncertainty with the systematic error analysis indicates that in this specific case of the M81 Cepheid observations, the photometry itself is still limiting the precision of the solution, not the small number of Cepheids. A factor of three improvement in the random error associated with the derived true distance modulus could have been obtained by our having acquiring better photometry on the two known Cepheids before the systematic effects of strip positioning and phasing would have been of comparable concern. The interesting result to emerge is that the sample size is not as big a limiting factor as one might naively assume. The behavior of Cepheids in phase and within the instability strip is such that in correcting for reddening using our multi-wavelength methodology we implicitly account for a major portion of those potentially large systematic errors occurring at the individual (uncorrected) wavelengths.

IV. THE COLOR-MAGNITUDE DIAGRAM AND TOTAL REDDENING

As noted in a recent paper (Madore and Freedman 1992), with the use of only a single (but deep) color-magnitude diagram it is possible to estimate a total average extinction to extragalactic systems using the color shift of the blue plume of stars defining the upper main sequence within the galaxy itself. We have done this independently for each of the two Cepheid fields. Restricting our attention to stars with $20.0 < V < 22.5$ mag (to obtain a sufficiently large sample of stars with moderately small measurement errors) and $(B - V) < 0.7$ mag (to eliminate highly evolved objects) we estimated the centerline of the blue plume to be $(B - V) = 0.14 \pm 0.03$ mag for the the V30 field, and $(B - V) = 0.05 \pm 0.01$ mag for the V2 field, with 43 and 64 stars contributing to the solutions respectively. Using the intrinsic color of the blue plume in IC 1613 (see Freedman 1988, where $(B - V)_\circ = -0.25$ mag) as fiducial, we then derive reddenings of $E(B - V) = 0.39$ and 0.30 mag for the V30 and V2 fields, respectively. These values are not unlike those derived by Zickgraph & Humphreys (1991) in their photographic study of the bright star population of M81; nevertheless these are large-scale averages, and given the patchy nature of dust lanes, these ensemble averages, quoted above, should be treated with care, as they may or may not be applicable to any given object or other classes of objects in the same galaxy.

V. LUMINOSITY FUNCTIONS

As a final note, we present here the luminosity functions for the main-sequence population of stars in the two Cepheid fields in M81. In her study of the luminosity functions of the brightest blue stars in nearby galaxies Freedman (1985) noted that only one galaxy deviated significantly in the slope of its luminosity function; that galaxy was M81. However, in the case of M81 the limiting magnitude of the photographic survey was rather shallow, and that was the galaxy for which the photometric calibration was the least secure. Although more limited in areal coverage, the CCD data presented in this paper go deeper, and do represent a step forward in photometric accuracy over the original photographic study.

Following the precepts of Freedman (19S5) the blue plume stars were selected by a red color cut-off designed to compensate for the average line-of-sigllt reddening, eliminate foreground stars in our galaxy, and exclude highly evolved stars in the: parent galaxy, without significantly depleting the numbers of stars making up any given magnitude bin down the main sequence. The results are shown for each of the two Cepheid fields in Figure *. The data for the V2 field are off-set from the V30 data by 1.5 in log N, where the last bins in both cases have about 100 stars contributing to them. The solid lines arc not formal fits to the data but rather lines of slope 0.67 as found to be generally applicable to other nearby galaxy bright-star luminosity functions. As can be seen these lines do represent the new data sufficiently well that there is now no reason to believe that M81 harbors a population of stars anomalous in this mass function **at** the bright end. Similar conclusions have been reached by Zickgraf & Humphreys (1 991).

VI. CONCLUSIONS

Based on BVRI data acquired for two thirty-day Cepheids in M81 a robust estimate of the true distance modulus to this galaxy has been determined to be 27.75 msg. Systematic errors duc to random phase and incomplete filling of the instability strip account for less than 0.1 mag of uncertainty. Photometric errors, assessed from independently processing repeat observations of the same stars on consecutive nights, to derive independent distance modulus solutions arc the dominant source of random error, amounting to ± 0.28 mag (i.e., 14% in distance).

The main sequence luminosity functions in each of the two Cepheid fields of M81 arc found to be consistent with the universal slope of $\Delta \log N/\Delta V = 0.67$ found for the brightest stars in the blue plume of other nearby galaxies, analyzed in a self-consistent manner.

Acknowledgements

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References

Burstein, D., and Heiles, C. 1984, *Ap. J. Suppl.*, 54, 33.

Cardelli, J. A., Clayton, G. C., & Mathis, J.S. 1989, ApJ, 345, 245

Freedman, W. L. 1985, ApJ, 299, 74

Freedman, W. L. 1988, ApJ, 326, 691

Freedman, W. L. 1988, *A. J.*, 96, 1248

Freedman, W. L., & Madore, B. F. 1988, ApJL, 332, L63

Landolt, A. 1983, AJ, 88, 439

Madore, B. F., & Freedman, W. L. 1991, PASP, 103, 933

Madore, B. F., & Freedman, W. L. 1992, PASP, 104, 362

Ripero, * 1993 IAU Circ., **, I***.

Sandage, A. R. 1984, AJ, 89, 621

Schmidt-Kaler, Th. 1982, *Landolt-Bornstein*, New Series Vol. 2,

eds. *K.* Schaifers and H. H. Voigt, (Heidelberg: Springer-Verlag), p. 1

Wilson, C., Freedman, W. L., & Madore, B. F. 1990, AJ, 99, 149

Zickgraf, F. & Humphreys, R.M. 1991, AJ, 102, 113

Figure Caption

Fig. 1 - A reproduction of a plate of MS] take at the prime focus of the *CFHT*. The areas marked correspond to the regions over which stellar photometry was obtained on the CC]) frames shown in detail in Figures 2 and 3. North is at the top, cast to the left. The CCD frame as marked is 2,1 by 3.4 arcmin.

Fig. *2*- A reproduction of the V-band CCD frame centered on V2 in M81, showing the identifications of the dozen or so brightest stars identified by their numbers in 'J'able *.

Fig. 3 – A reproduction of the V-band CC]) frame centered on V30 in M81, showing the identifications of the dozen or so brightest stars identified by their numbers in Table *.

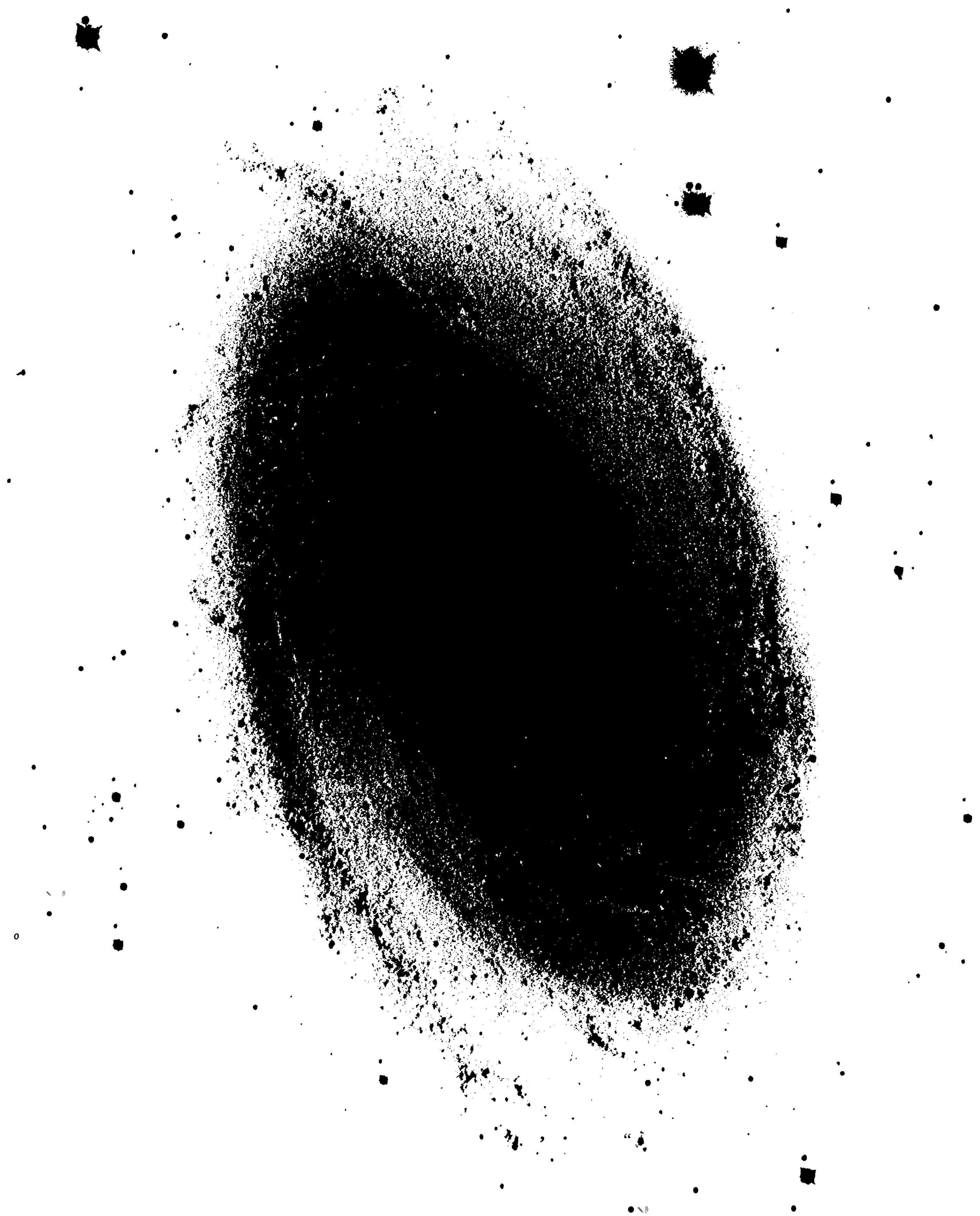
Fig. 4 – BVRI apparent distance moduli to M81 plotted as a function of inverse wavelength. The error bars arc in tile ratio of the intrinsic widths of the 1'1, relations at that wavelength. The dashed line is chi-squared minimization fit of a Galactic extinction law to the data, corresponding to a reddening of $E(B-V) = 0.**$ mag, giving a true distance modulus for M81 of 27.77 mag from the long wavelength intercept.

Fig. 5-- A schematic showing the worst-possible case scenario that would have to obtain in order for the two Cepheids observed in M81 to be maximally reddened and yet still give rise to a flat (apparently unreddened) multiwavelength modulus solution.

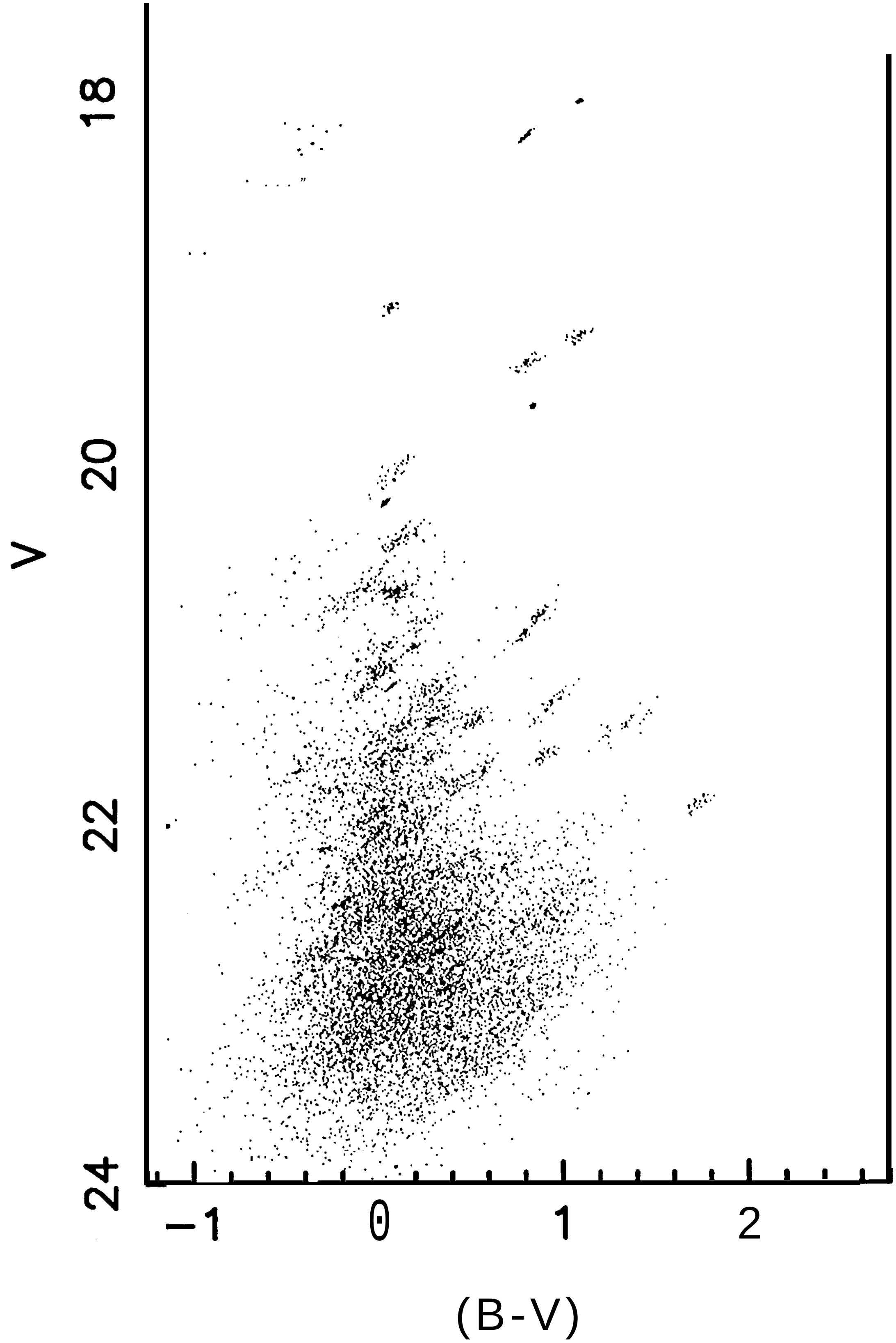
Fig, 6 - The color–magnitude diagram for the stars in the V2 Field of M81 as given in 'J'able *. The vertical line shows the position of the blue plume shifted by $E(B-V) = 0.39$ mag so as to fit the M81 data. The individual data points are ploted as bivariate, grcy-scale, gaussian distribution functions, so as to explicitly show the error ellipse associated with each star's magnitude and color. The degree to which tile error ellipses arc tipped is a function of the relative contribution of the B and V errors to the color.

Fig. 7- The color- magnitude diagram for the stars in the V30 Field of M81 as given in 'J'able *. The vertical line shows the position of the blue plume shifted by $E(B - V) = 0.30$ mag so as to fit the M81 data.

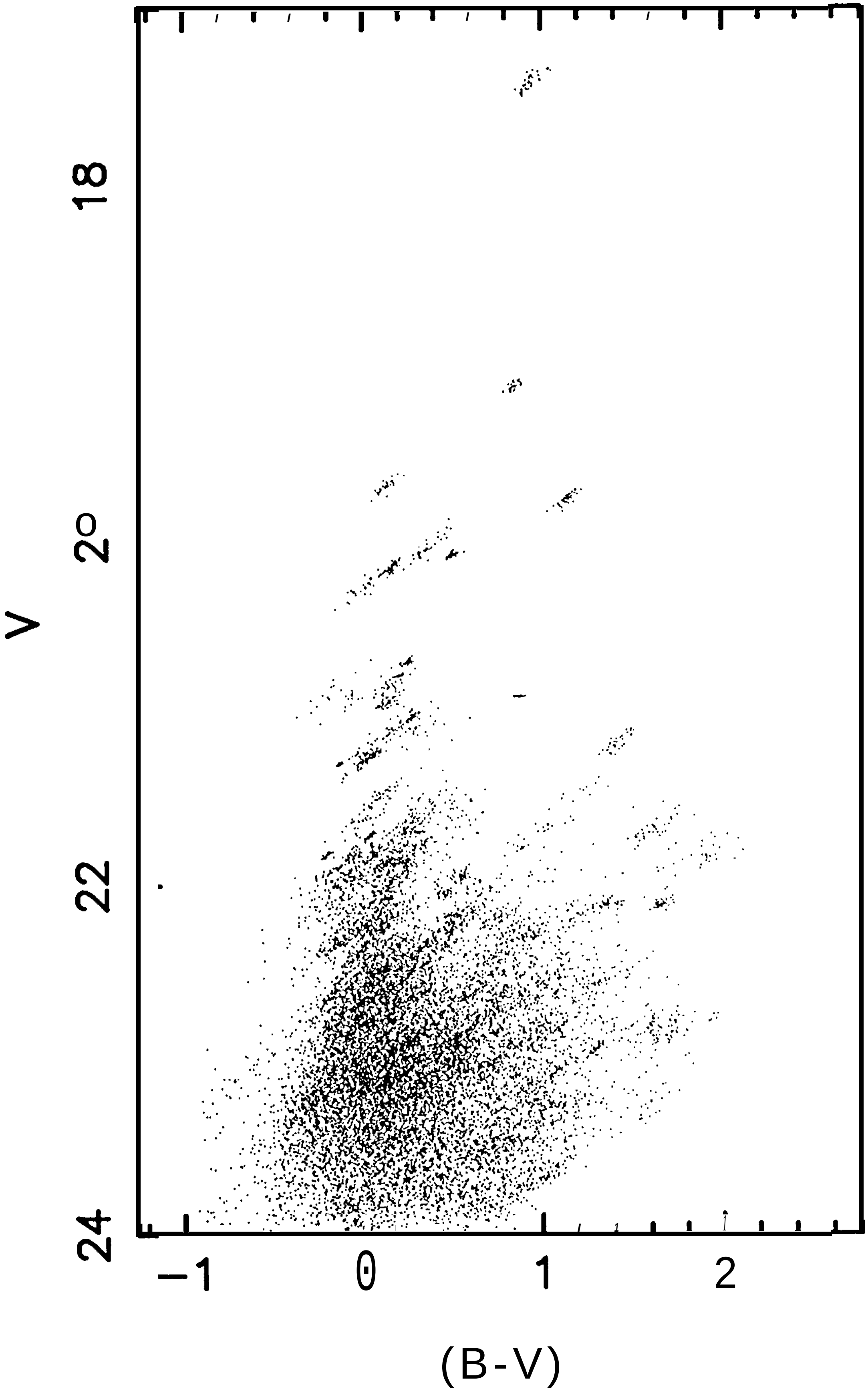
Fig. 8- 'The logarithmic luminosity function for the blue stars in two fields in M81 (V2: $(B - V) \leq 0.8$ mag; V30: $(B - V) \leq 0.**$mag). The solid line has a slope of 0.67, equal to that found by Freedman (1985) to be representative of luminosity functions for a sample of 10 nearby galaxies. The V2 data arc offset downward by 1.5 in log N with respect to the V30 data, for which the vertical scale is correct..

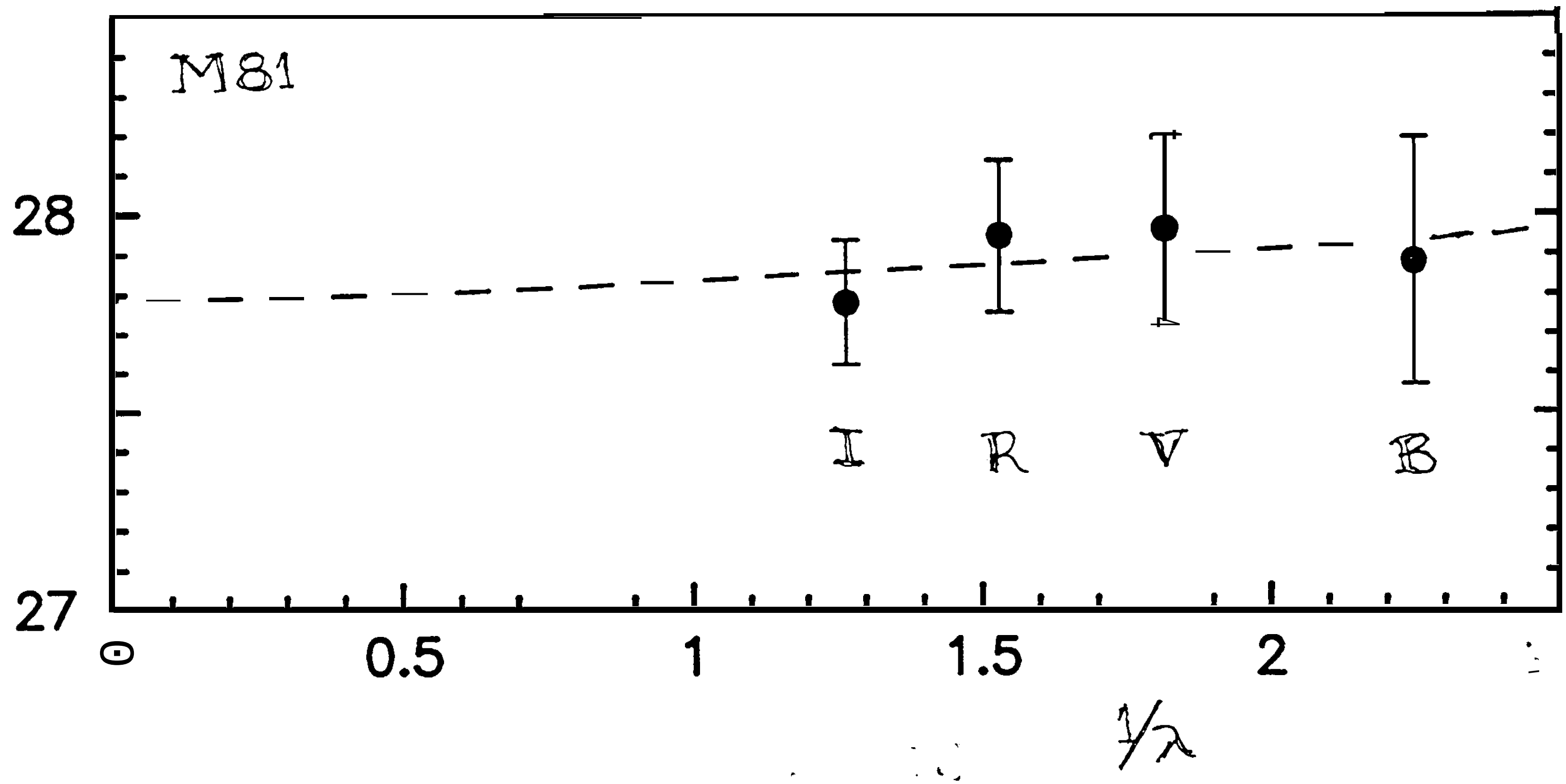


M81 V2 FIELD



M81 V30 FIELD




M81
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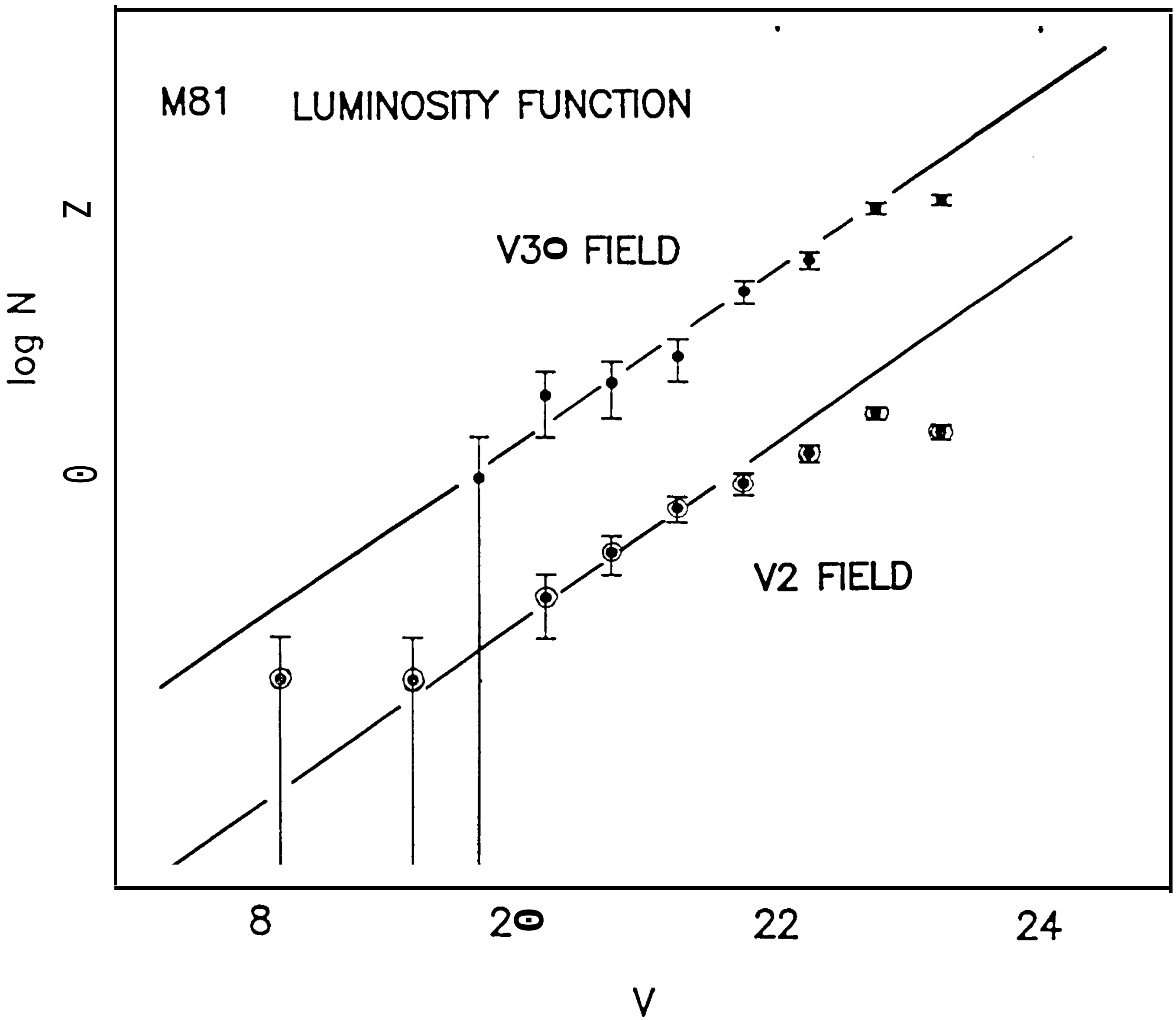
M81 LUMINOSITY FUNCTION
V3O FIELD
V2 FIELD
log N
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24
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